GEOLOGY AND PERMAFROST IN REALATION TO HYDROLOGY AND GEOPHYSICS

BY

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Geology and Permafrost in Relation to Hydrology and Geophysics

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Abstract

The complexity of the geologic framework within which the hydrologist and the geophysicist work is greatly increased in permafrost regions by the diversity of soil-water-ice conditions embraced by the term, "permafrost," by the complex distribution of permafrost, and by the complex distribution of ground ice within the permafrost.

The high costs of drilling in unsettled northern regions will necessitate heavy dependence on geophysical techniques in any regional inventories of geology, the distribution of permafrost and ground ice hydrology. Emphasis will be on light, portable, or airborne instrumentation. The selection of geophysical techniques and the design of instrumentation must be based on valid conceptual models of the distribution of geologic materials, permafrost and ground ice, and the models will vary greatly according to geologic, climatic, and hydrologic history of the particular area concerned.

Hydrologic studies in the permafrost regions of northern Canada are still in the preliminary surface stages. Integrated studies of the surface, active layer, and subpermafrost hydrologic regime have scarcely begun. Paleohydrology study of the changing hydrology regime during development of permafrost is an important key to understanding the distribution of permafrost and ground ice, but remains an underexploited field of research.

Introduction

In the non-permafrost regions, the geophysicist and the hydrologist are constantly being challenged by the complexities of the three-dimensional geological framework within which they work. The challenges are another order greater where the familiar physical properties of the geological materials may be radically altered by the existence of permafrost conditions. The most important factors giving rise to such complexity can be discussed under three headings: 1) the diversity of permafrost; 2) the distribution of permafrost; 3) the distribution of ground ice.

The Diversity of Permafrost

Permafrost is described as, "the thermal condition of earth materials such as soil and rock when their temperature remains below 32° continuously for a number of years," (Brown, 1970, p.1). But the significant factor is the sum-total of the geologic material

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itself, its water content (if any), and the state of the water. Permanently frozen rock, for example some granites, may have no porosity, and hence no water in any state. In highly porous materials such as gravel, voids may contain a limited amount of hoar frost plus water vapour (the "dry permafrost")of Klondike placer miners, or be wholly occupied by ice. Soil-water-ice combinations are common in glacial lake clay and some clay-rich tills with three-dimensional reticulate networks of ice surrounding blocks of unfrozen clay; or contained water may be completely unfrozen because of pressure, salinity, or capillary attraction to the soil. From the above examples, it will be seen that permafrost affects diverse geologic materials in diverse ways, so that there can be no simple pattern to the way in which the permafrost condition changes the physical properties of familiar geologic materials.

Distribution of Permafrost

Permafrost underlies about half the land area of Canada. The permafrost region can be divided into two zones: discontinuous in the south; and continuous in the north (Brown, 1967). At the southern limit of the discontinuous zone, permafrost consists of small patches of a few feet, or tens of feet thick. A large number of factors--other than climate--affect distribution of permafrost, including physical properties of the geologic materials, vegetation cover, winter snow cover, aspect, and the presence or absence of surface water, or moving ground water. Depending upon relative importance of these factors, the southernmost outliers of permafrost may be in windswept hilltops--the case around Schefferville, P. Q., or in the peat bogs, the common cas in the Interior Plains, or in north-facing slopes.

Permafrost becomes thicker and more continuous northward, but through taliks or windows in the permafrost are numerous far north into the continuous zone. These are mostly beneath streams, ponds, and lakes which do not freeze to the bottom; a few such taliks are maintained by convective transfer or heat due to infiltration of surface waters into highly permeable material (such as jointed carbonate rocks or sandstones that lack drift cover).

Boundaries between permanently frozen and unfrozen material rarely coincide with boundaries between geologic units. As a result, expecially in the discontinuous zone, almost every geologic unit is encountered in both frozen and unfrozen (and sometimes intermediate) states, more than doubling the effective number of units that may be encountered.

Distribution of Ground Ice

Ground ice occurs in a bewildering array of forms within a wide range of geologic materials. Almost all permanently frozen soil or rock, having significant porosity, contains pore ice that completely occupies voids (note, however, exceptions such as "dry permafrost," (rare), and the widespread occurrence of unfrozen moisture in clay). Of greater interest is ice in excess of that required to fill porosity. Such ice occurs in forms ranging from lenses and veins a millimetre or two thick, to massive tabular bodies up to 140 feet thick (Mackay, 1972, Fig. 17, p. 16), massive, irregularly-shaped bodies, and extensive systems of ice-wedges.

The distribution and form of ground ice is the product of a number of conditions beyond those required for development of permafrost; the most important of these are: 1) grain-size, porosity and permeability of the soil and rock materials; 2) the origin and post-depositional history of the geologic units involved; 3) the spatial relationships of those geologic units; 4) hydrologic conditions from the onset of permafrost to the present.

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These factors are all interrelated. A classification of ground ice by Mackay, (1972, Fig. 2, p. 4) contributes greatly to understanding of the interrelationships. The classification (Fig. 1) is based initially on origin of water prior to freezing, by which ground ice is divided into that derived from surface or atmospheric water, and that derived from subsurface water. In Figure 1, water within the active layer is placed in a separate category, even though it is, strictly speaking, subsurface water; the distinction is useful in understanding the origin of aggradational ice. In the first category, by far the most important types are single vein and ice-wedges. Single vein ice forms by gravity transfer of surface water into thermal contractions--cracks that develop seasonally in already permanently frozen materials. Ice-wedges develop by repeated tension cracking along the line of an original single vein. Requirements for their development are few: 1) complete bonding of the soil by pore ice so that cracking is localized along a few widely-spread lines; 2) shallow seasonal thaw (i.e. a shallow, active layer) so that seasonal increments to the ice-wedge are preserved. At lower altitudes, these conditions may obtain only in areas of relatively thick organic cover. At higher altitudes, even gravel with little or no vegetation cover may be completely bonded and have a sufficiently shallow active layer to permit ice-wedge development.

A broader range of factors controlled development of the second category of ground ice that developed from subsurface water. To understand the operation of those controls, it is important for any region, to go back to the period when the permafrost conditions existing there today were first developed. For extensive, stable surfaces in unglaciated northwest Yukon, this may date back to early in the Pleistocene epoch; or, if permafrost disappeared during major interglacial stages, it may date back to the beginning of the Wisconsinan stage. For most of the permafrost region of Canada, it dates back no further than the end of the Wisconsinan stage when the land area covered by Wisconsinan ice, and the glacial, glaciolacustrine, and glaciofluvial deposits of that stage were first subjected to invasion by permafrost following glacial retreat and drainage of glacial lakes.

Development of permafrost, *ab initio*, would have taken place under a wide range of geologic and hydrologic conditions with a consequent wide range in form, amount, and distribution of ground ice. A few examples of typical settings from Mackenzie Valley will illustrate typical cases.

Till plains, with a few feet to a few tens of feet of lodgment till overlying bedrock, constitute roughly 50% of the land surface of Mackenzie Valley. The till is typically sandy, clayey silt with low porosity and low permeability. With descent of a freezing plane into any soil material, one of two things can happen depending on grain-size, porosity, permeability of the material: 1) pore water freezes to form pore ice, with expulsion downward of the 10% excess water arising from volume expansion in freezing; or, 2) if pore pressures are sufficiently high in the soil, water migrates to the freezing plane and a lens of segregated ice is formed. Because of the relatively low permeability of till, expulsion of pore water with advance of the freezing plane would build up high pore pressures in the immediate subjacent till, which would be relieved by formation of a very thin lens of segregated ice. The freezing plane would then advance further until increasing pore pressure again favoured segregation, and so on. Thus, lodgment till typically has only a few thin subhorizontal lenses of segregated ice, (however, see further for comment on aggradational ice in till, and other fine-grained materials.)

Next in areal extent in Mackenzie Valley are glaciolacustrine silt, clay, and minor sand deposited in glacial lakes that occur extensively along the valley axis. Glaciofluvial deltas occur intermittently along the margins of the former glacial lakes, and gravel and sand of the deltas interfinger with the glacial lake sediments (Fig. 2); sand was spread outward as a veneer over the glaciolacustrine

sediments as the glacial lakes shallowed by differential isostatic uplift and/or downcutting of outlets.

With onset of permfrost conditions, the freezing plane would move downward through the sand veneer, producing pore ice and expelling pore water. Segregated ice would develop when the interface encountered underlying silt, growth continuing as long as groundwater was supplied through permeable interfingering beds of sand and gravel. It is probable that sand and gravel of the glaciofluvial deltas remained at least locally unfrozen and permeable for a long time after initial invasion of the glaciolacustrine sediments by permafrost. In the discontinuous zone today, many of the glaciofluvial deposits remain unfrozen, or have through taliks, even though adjacent glaciolacustrine sediments are permanently frozen to 100 feet or more. Convective transfer of heat by infiltrating groundwater appears to be primarily responsible. Additionally, most of the glaciofluvial deltas are crossed by major streams. Unfrozen zones beneath the stream channels would have permitted ingress of surface water, at least until the streams became incised into their deltas, with consequent loss of hydraulic gradient.

In Figure 2C, the 0°C interface is shown as having passed downward through clay with the clay remaining unfrozen. However, with deeper penetration of the 0°C interface and reduction of temperature in the clay layer, segregated ice could develop. Commonly, the segregated ice forms a reticulate network around unfrozen blocks of clay having relatively low moisture. The mechanism by which segregation is localized in veins forming the network has not been investigated. However, the low moisture content of the clay suggests that the necessary water was derived from the clay rather than from an external source, and the typical very coarse-grained character of the ice suggests that migration of the water was very slow.

One or more ice layers, commonly one or two met in aggregate thickness, underlie most permanently frozen peat. Development of the ice is a special case of ice segregation. Apparently, development of permafrost in a tract of wet organic terrain begins at numerous small slightly-elevated centres. When permafrost extends downward to mineral soil, ice segregation takes place, producing domed forms called palsas. Under suitable conditions, the palsas can expand peripherally to form broad peat plateaus, and ultimately, the peat plateaus can coalesce into peat plains. Throughout the process, up to final coalescence, water to form the segregated ice is derived from immediately adjacent wet, unfrozen organic terrain. Therefore, no requirement for a permeable aquifer to conduct water to the base of the developing ice lens from an external source.

Hummocky to rolling dead-ice moraine, another widely-occurring terrain unit, presents still another pattern of distribution of ground ice. The dead-ice moraine consists of ablation till with highly irregular lenses of silt, sand, and gravel. Primary topography is also highly irregular, so that at onset of permafrost conditions, both geologic and hydrologic conditions were very complicated. The result is very irregularly-shaped and erratically-distributed bodies of massive ice. Much of the ice may be segregated epigenitic ice, but some may be intrusive.

According to Mackay (1972, p. 10), intrusive (injection) ice is formed by intrusion of water under pressure, and its freezing to uplift the ground above it. The forms of intrusive ice are analagous to those of igneous intrusives, i.e. sills, domed laccolith-like forms, or discordant forms, as in some pingo ice. The pressure may be entirely hydrostatic (as in open-system pingos), or may develop when thaw bulbs, or through taliks, become enclosed by permafrost; the pressure develops as water is expelled on developmentof pore ice as permafrost encroaches on permeable materials within the thaw bulb or talik. The thaw bulbs and taliks may be primary, i.e. they are the last remnants of unfrozen ground during original development or permafrost. Many, however, are secondary in that they underlie thermokarst lakes that developed on previously permanently-frozen

ice-rich sediments. Most closed-system pingos appear to have developed by drainage of thermakarst lakes and refreezing of thawed sediments beneath them (Mackay, 1973, p. 71).

There are major difficulties in distinguishing between segregated and intrusive ice. Mackay (1966, p. 61) suggested relative purity of intrusive ice, and geomorphic settings, as distinguishing features. However, ice underlying some domed palsas is remarkably pure, even where the palsas are islands of permafrost surrounded by unfrozen terrain, ruling out any possibility of pressure within a closed system. Further, although Mackay (1966, Table I; 1972, Fig. 2) has classified pingo ice as being of intrusive (injection) origin, he has more recently suggested (Mackay, 1973, p. 999) that "segregated ice is more important to pingo growth than injection ice."

Aggradational ice results when the upper surface of the permafrost rises, incorporating ice lenses formed at the base of the active layer (Mackay 1972, p. 10). The top of the permafrost may rise in response to climatic cooling, to revegetation following a fire, or in response to aggradation of the land surface. Aggradational ice occurs in virtually all permafrost terrain that is underlain by fine-grained materials. In the glaciated Interior Plains, this includes till plains, glaciolacustrine plains, till of dead-ice moraines, and most alluvial plains and terraces - excluding only glaciofluvial deposits and peatlands, so that some 75% or more of the near surface material contains aggradational ice. Fine-grained sediments, including the products of rock-weathering, alluvial silts, and loess veneers, occupy the near surface in a comparable proportion of the unglaciated region.

The formerly greater depth of the active layer can commonly be recognized by buried organic layers, or stringers of organic material incorporated into the soil by cryoturbation. The lower limit of such organic material commonly coincides with a boundary having soil with abundant thin lenses of segregated ice above, and conspicuously less ice below. Except in exceptional circumstances, as in thick accumulations of slopewash silt in depressions, aggradational ice is typically restricted to a zone 1/2 to 2 m. thick beneath the active layer. Because it is so widespread, it probably exceeds in volume all the more spectacular forms of ground ice. Fortunately, where other forms of ground ice are absent at greater depths, there are rather readily definable limits to the damage than can be incurred by degradation of aggradational ice.

Permafrost and the Hydrologist

There are two approaches that the hydrologist might take to permafrost--the first, adequate for many practical purposes, would be to treat permafrost as an impermeable material to be ignored, and proceed to investigate surface hydrology, and the hydrology of the active layer, taliks, and the unfrozen subpermafrost zone. This would require a knowledge of distribution of permafrost, hopefully to be supplied by geographers, geologists, and geophysicists. The distribution, form, and origin of ground ice within the permafrost could be totally ignored.

Hopefully, hydrologists will take a second approach and investigate the role of hydrology in determining distribution of permafrost and ground ice, thus increasing predictive capability. For example, the maintenance of taliks beneath water bodies may be treated as a heat conduction problem, but clearly, maintenance of taliks in permeable glaciofluvial deposits, or in jointed bedrock, involves convective transfer of heat by infiltration of surface water into the groundwater system, and is a problem clearly within the rightful field of hydrologists.

In investigating distribution of ground ice, there are two approaches open to hydrologists--the first is one kind of paleohydrology, i.e. reconstruction of the hydrologic regime at the onset of primary development of permafrost, and changes in the regime as subsurface hydrology was progressively restricted by permafrost; the second approach is investigation of present day examples of permafrost invasion.

Examples studied to date such as permafrost invasion of alluvium following shifting of a stream channel (Smith, 1973), and invasion following drainage of a lake (Mackay, 1973). Such cases are amenable to treatment as heat conduction problems, but the studies would be enhanced by addition of the approach of the groundwater hydrologist, with monitoring of pressures, determination of permeability and porosity of the unfrozen sediments, and the use of tracers to follow the migration of water from the sediments to the freezing interface where ice segregation takes place.

The active layer warrants further investigation, not only for its unique role as a seasonal aquifer, but also for its role in the development of aggradational ice, noted earlier as being probably the commonest form of segregated ice. The movement of water through unfrozen fens, partly on the surface, and partly through organic material in the subsurface, constitutes still another subject for investigation, having practical importance, for example where highway fill loaded on the organic material reduces permeability of the organic material and forces water flow to the surface.

Much emphasis is placed on preservation of permafrost in order to avoid environmental damage. Nevertheless, there is considerable scope for beneficial manipulation of permafrost. For example, Dawson, Y. T. obtains its water supply from permeable unfrozen gravel situated within the thaw bulb associated with the Klondike River, and similar sources are possible for other northern communities. However, unless the thaw bulb extends for a considerable distance back from the river bank, the necessary well and connecting line must be placed immediately adjacent to the river bank where potential for damage due to bank erosion is high. Limited drilling suggests that this would be the case, for example, at Old Crow, Y. T. A possible solution is to thaw a "conduit" of permeable gravel to beneath a suitable wellsite a safe distance from the bank. The technology for thawing such a conduit can be adapted readily from the cold water thawing procedures used for over 35 years in the placer mining industry in the Klondike District. Provided that sufficient flow of water is maintained in the conduit by pumping, the conduit should remain unfrozen indefinitely.

Other northern communities may be situated on permanently frozen gravel, sand, sandstone, or jointed limestone which lack thaw bulbs. The same cold water technique could be used to develop artificial thaw bulbs to serve as groundwater reservoirs which could be recharged during the brief Arctic summer when surfacing water is available. Such manipulation of permafrost, of course, is only feasible in geologic materials that are stable when thawed, such as rock, sand, or gravel.

Permafrost and the Geophysicist

In the non-permafrost areas, geophysical techniques, especially shallow seismic, resistivity, and borehole logging are widely used in surficial geology and subsurface hydrology. In the remote permafrost regions, potential use of portable surface, or airborne geophysical techniques is particularly attractive because of the high cost of drilling. Surface resistivity and shallow seismic techniques have already proved valuable in determining areal extent and depth of permafrost. Density logging of test holes has been used for determining vertical distribution of ice, without recourse to costly coring and subsequent laboratory examination, and gravity profiling shows promise for delineating massive ice bodies (V. N. Rampton, personal communication).

However, available techniques lack the precision needed to detect and delineate irregularly-shaped and erratically-distributed massive ice, for example the type found in hummocky moraine belts, or to detect and delineate polygonal ice-wedge

systems where surface expression of them is lacking. Distinction between various soil-ice and soil-ice-water combinations will doubtless prove difficult, particularly where variability in ice and water content are compounded by both vertical and horizontal variability of the geologic materials.

From the point of view of a geologist, two approaches seem important for enhancing the utility of geophysics in permafrost investigation. Firstly, geophysical techniques (more likely combinations of techniques), and accompanying instrumentation, must be tailored to specific conceptual models of the distribution of geologic materials, permafrost and ground ice. Secondly, measurement of physical properties of naturally-occurring soil ice and soil-ice-water combinations at the range of temperatures prevailing in permafrost areas requires further investigation. Kurfurst (1973) is currently measuring ultrasonic wave velocities in frozen cores. Measurement of other properties, especially resistivity, is required, and possible anisotropy of physical properties due to orientation of segregated ice should be investigated.

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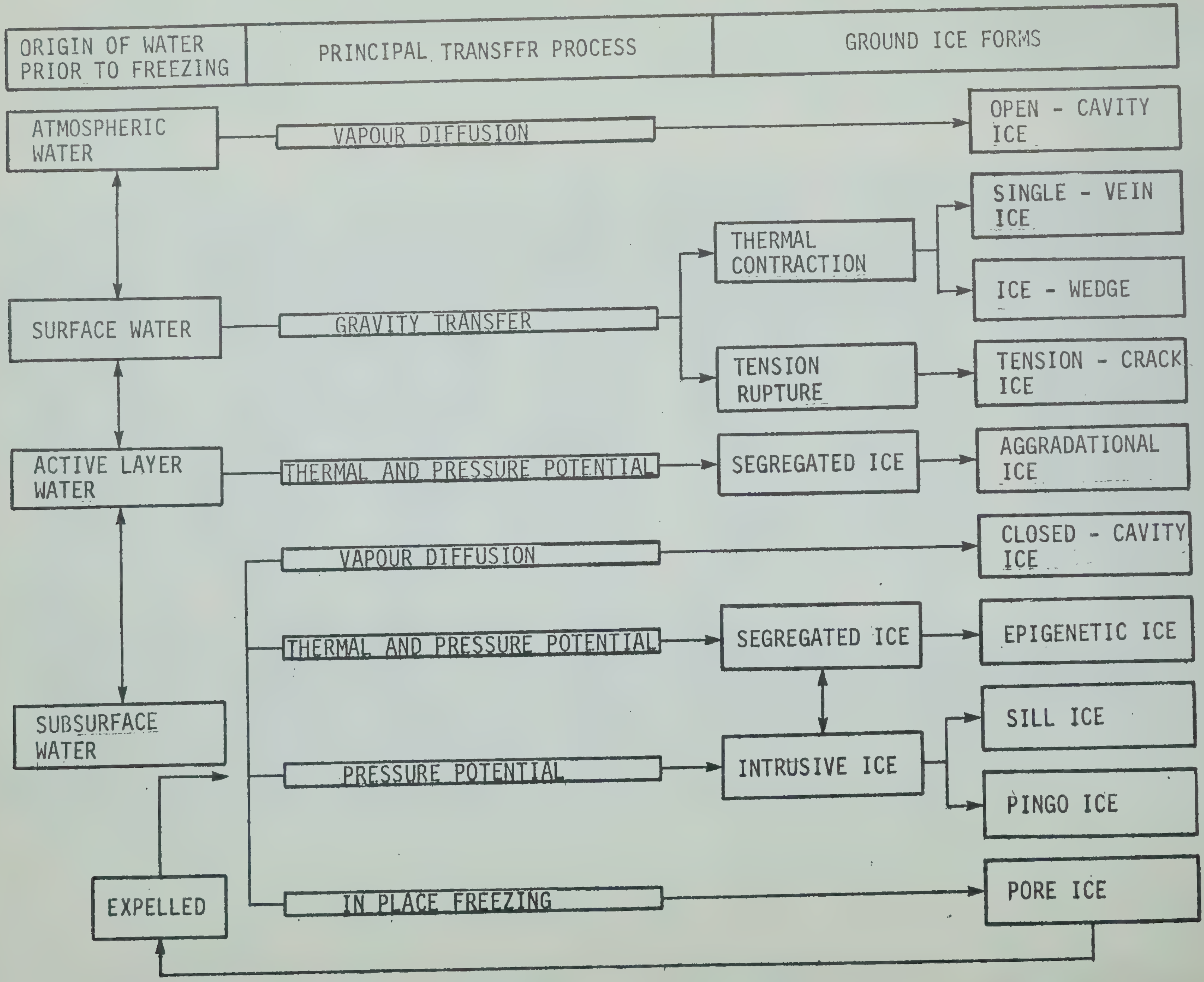

Figure 1. Classification of underground ice

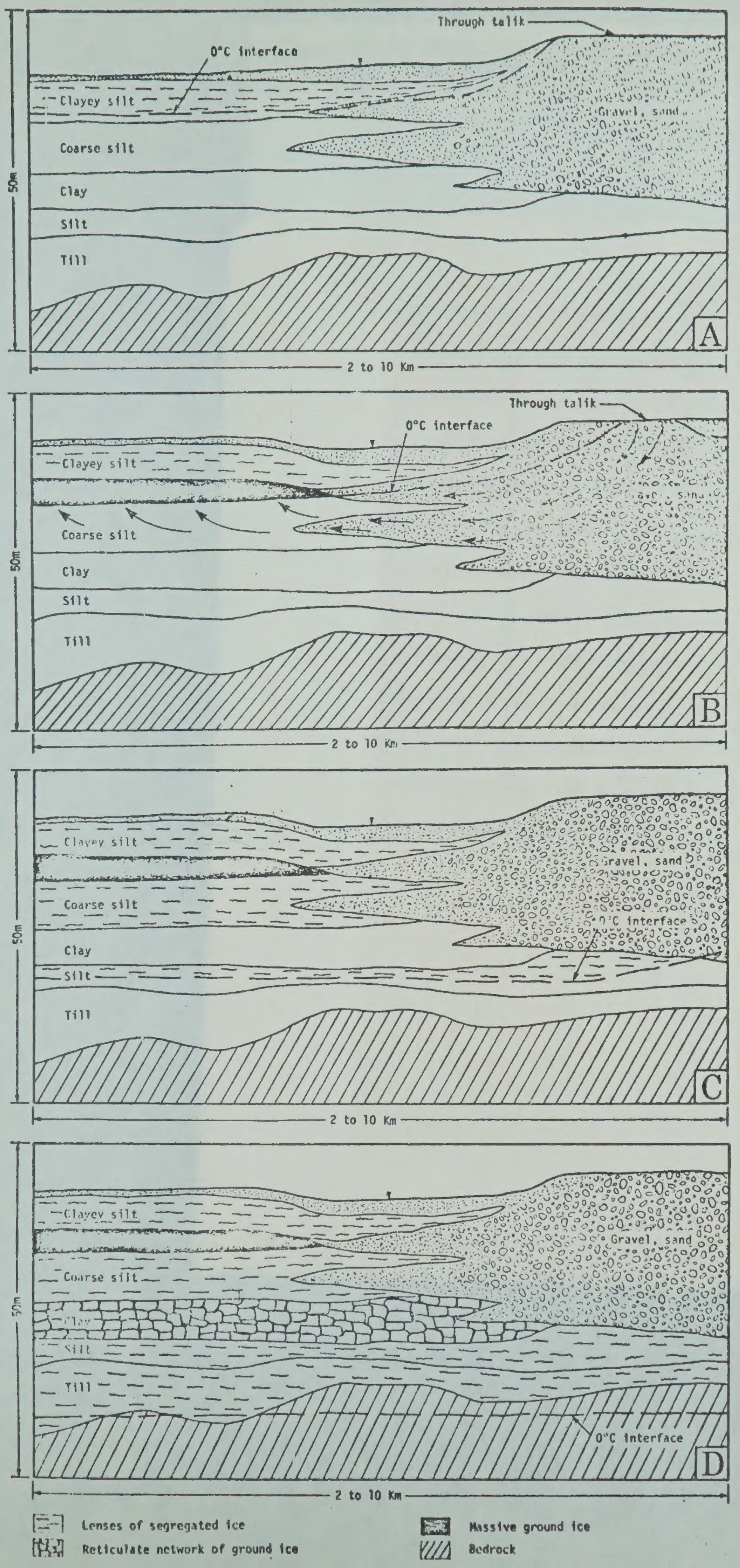

Figure 2. Development of ground ice in glaciolacustrine sediments adjacent to a glaciofluvial delta.

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